# Testing new physics with neutrino oscillation experiments

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Fermilab Theory Seminar
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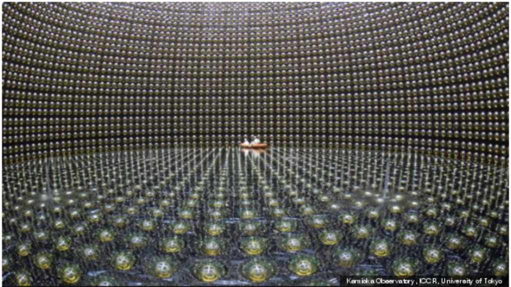
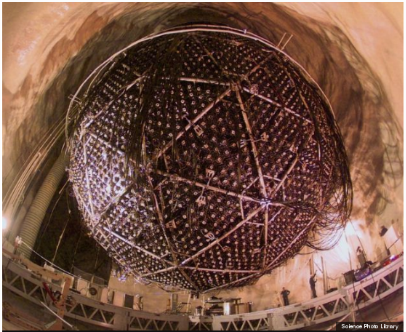
# Neutrino 'flip' wins physics Nobel Prize

By Jonathan Webb
Science reporter, BBC News

6 October 2015 | Science & Environment


Kamioka Observatory, ICRR, University of Tokyo

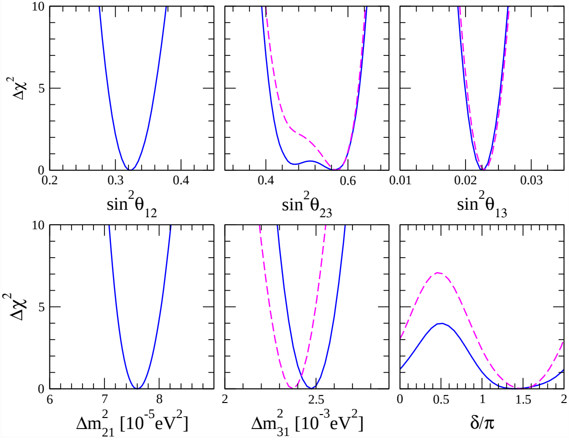
Crucial measurements were made at the Super-Kamiokande neutrino detector in Japan


Science Photo Library

The Sudbury Neutrino Observatory, like Super-K, is housed in a cavern inside a mine

# Neutrino Oscillation Global Fit Results

D.V.Forero, Tórtola & Valle (PRD **90**(2014)) arxiv:1405.7540




| parameter | bf$\pm$ 1$\sigma$ | |
|---|---|---|
| $\Delta m^2_{21}$ [$10^{-5}$eV$^2$] | $7.60^{+0.19}_{-0.18}$ | 2.4% |
| $\|\Delta m^2_{31}\|$[$10^{-3}$eV$^2$] | $2.48^{+0.05}_{-0.07}$ | 2.4% |
| IH | $2.38^{+0.05}_{-0.06}$ | |
| $\sin^2\theta_{12}/10^{-1}$ | $3.23 \pm 0.16$ | 5.0% |
| $\sin^2\theta_{13}/10^{-2}$ | $2.26 \pm 0.12$ | 5.3% |
| IH | $2.29 \pm 0.12$ | 5.2% |
| $\sin^2\theta_{23}/10^{-1}$ | $5.67^{+0.32}_{-1.24}$ | 7.4% |
| IH | $5.73^{+0.25}_{-0.39}$ | 6.9% |
| $\delta/\pi$ | $1.41^{+0.55}_{-0.40}$ | |
| IH | $1.48 \pm 0.31$ | |

# The topics along this talk...

1. Introduction
   - Is it possible to generate a ‘large’ NSI?

2. NSI phenomenology
   - The standard approach to the NSI
   - What are the current limits?
   - Where the CC-like NSI can be probed?
   - Results I
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   - Are there any implications for the future $\nu$-program?

# The beginnings

## The importance of neutrino–matter interactions

L. Wolfenstein (PRD **17**(1978))

$m_\nu = 0$

- Case I: Off-diagonal NC couplings.
- Case II: Non-orthogonality among the $\nu$s in the weak basis.

Vacuum and matter $\nu$-oscillations

- Case III: NC with diagonal couplings but including the $\nu_e$-CC interactions with matter, Standard matter effect.

J.W.F Valle (PLB **199**(1987))

- Neutrinos remain massless due to a symmetry (total LN).
- Because of the Non-unitarity of the leptonic mixing matrix, the flavor neutrino eigenstates are not orthogonal.
- In matter 'oscillations' appear due to the interplay of CC and NC $\nu$–interactions.

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# Towers of effective operators

$\Lambda > \Lambda_{EWSB}$

M.B. Gavela *et al.* (PRD **79**(2009))

$$\delta\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2}\sum_i^{d=6}\mathcal{C}_i\,\mathcal{O}_i^{d=6} + \frac{1}{\Lambda^4}\sum_k^{d=8}\mathcal{C}_k\,\mathcal{O}_k^{d=8}\,,$$

After EWSB:

$$\epsilon^{m,L}_{\beta\alpha} = \frac{v^2}{2\Lambda^2}\left(\mathcal{C}_{\text{NSI}}^{\bar{L}L\bar{L}L}\right)^{\alpha e}_{\beta e}\,,\quad \epsilon^{m,R}_{\beta\alpha} = \frac{v^2}{2\Lambda^2}\left(-\frac{1}{2}\mathcal{C}_{LE} + \frac{v^2}{2\Lambda^2}(\mathcal{C}^{\mathbf{1}}_{LEH} + \mathcal{C}^{\mathbf{3}}_{LEH})\right)^{\alpha e}_{\beta e}\,,$$

where the conditions to suppress charged LFV (4 lepton) process are:

$$\left(-\frac{1}{2}\mathcal{C}_{LE} + \frac{v^2}{2\Lambda^2}(\mathcal{C}^{\mathbf{1}}_{LEH} - \mathcal{C}^{\mathbf{3}}_{LEH})\right)^{\alpha\gamma}_{\beta\delta} = 0\,,$$

$$\left(\mathcal{C}^{\mathbf{1}}_{LL} + \mathcal{C}^{\mathbf{3}}_{LL} + \frac{v^2}{2\Lambda^2}\left(\mathcal{C}^{\mathbf{111}}_{LLH} + \mathcal{C}^{\mathbf{331}}_{LLH} - \mathcal{C}^{\mathbf{133}}_{LLH} - \mathcal{C}^{\mathbf{313}}_{LLH}\right)\right)^{\alpha\gamma}_{\beta\delta} = 0\,,$$

# Towers of effective operators

$\Lambda > \Lambda_{EWSB}$

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Assumptions, limitations and consequences of the analysis:

- The analysis is limited to operators induced at *tree level*.
- With $d = 6$ operators (obeying the cancellation rules) it is not possible to obtain all the NSI couplings, for instance, $\varepsilon^{m}_{e\tau}$.
- The $d = 8$ operators (obeying the cancellation rules) are the potential candidates to generate 'large' NSI.
- For $d = 8$, and the mediators (2 to do the cancellation job) coupling to only SM bilinears, $d = 6$ contributions are also produced. Thus, some fine-tuning or extra symmetries are need.
- In a $d = 8$ case fulfilling all the requirements one should be careful with one-loop corrections since they can spoil the $d = 6$ cancellation conditions.

Many requirements (and some fine-tuning) have to be fulfilled to generate 'large NSI' when $\Lambda$ is above the EWSB scale. Are there another possibilities?

# NSI via light mediators, $m_X \ll m_Z$

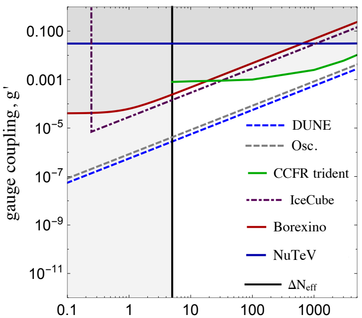
Y. Farzan *et al.* arxiv:1512.09147

New light gauge boson from U(1)' gauge models with a non-trivial two component representation for the left-handed leptons:

- From the low energy relation: $\varepsilon G_F \sim (g_X/m_X)^2$, to generate $\varepsilon \sim 1$, the condition $g_X/m_X = G_F^{1/2}$ should be fulfilled.

The non-detection of the new particle implies:

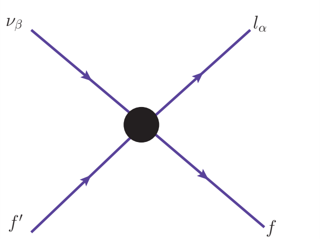
- Instead of the usual requirement $m_X \gg m_Z$ (which produces $\varepsilon \ll 1$), a second option considers $g_X \ll 1$. Specifically, $g_X \sim 5 \times 10^{-5}$ and $m_X \sim 10\,\text{MeV}$.

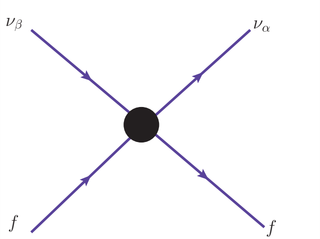


# Outline

# The standard NSI (pheno) framework

L. Wolfenstein (PRD **17**(1978)), J.W.F Valle (PLB **199**(1987))
M.M Guzzo *et al.* (PLB **260**(1991)), E. Roulet (PRD **44**(1991))




$$\mathcal{L}_{V\pm A} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\varepsilon}_{\alpha\beta}^{S(D),f,f',V\pm A} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5) \ell_\alpha\right] \left[\bar{f}' \gamma_\rho (1\pm\gamma^5) f\right]$$

$$+ \frac{G_F}{\sqrt{2}} \sum_{f} \tilde{\varepsilon}_{\alpha\beta}^{m,f,V\pm A} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5) \nu_\beta\right] \left[\bar{f} \gamma_\rho (1\pm\gamma^5) f\right] + \text{h.c.},$$

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# Current bounds

## CC-like NSI

C. Biggio *et al.* (JHEP **090** (2009))

Bounds calculated from:

- $V^{ud}$ determination: From Kaon decays $\rightarrow$ $V^{us}$ (and asumming CKM unitarity) compared with the derivation from beta decays (affected by NSI).
- Universality tests: Ratios $\pi \rightarrow e(\mu)\nu$ and $\tau \rightarrow \pi\nu$ decay rates modified by quark CC-like NSI.
- Non-observation of flavor change at NOMAD ('zero distance effect'). Channels $\nu_\mu \rightarrow \nu_e$ ($|\varepsilon_{\mu e}^{ud\,A}|$, $|\varepsilon_{e\mu}^{ud\,L(R)}|$), $\nu_e \rightarrow \nu_\tau$ ($|\varepsilon_{\tau e}^{ud}|$), and $\nu_\mu \rightarrow \nu_\tau$ ($|\varepsilon_{\mu\tau}^{ud\,A}|$, $|\varepsilon_{\tau\mu}^{ud\,L(R)}|$).

Assuming only one parameter at a time (90% C.L. for 1 d.o.f):

$$\mathcal{X} = \begin{bmatrix} V & L(R) & V \\ A & A & A \\ L(R) & L(R) & A \end{bmatrix}, \; |\varepsilon_{\alpha\beta}^{ud\,\mathcal{X}_{ij}}| < \begin{bmatrix} \boxed{0.041} & 0.026(0.037) & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.087(0.12) & 0.013(0.018) & 0.13 \end{bmatrix}$$

WARNING: Use these limits with care! Are the assumptions clear?

We improved the limit on $|\varepsilon_{ee}^{ud}|$ NSI coupling (it will be covered later on).

# Current bounds

## NC-like NSI

M.C. Gonzalez-Garcia *et al.* (JHEP **152**(2013))

From a global fit of oscillation neutrino data, the 90% of C.L bounds for the LMA solution are:

$$\varepsilon_{\alpha\beta} - \varepsilon_{\mu\mu}\Big|^{f=d(u)} \in \begin{bmatrix} [0.02(0.00), 0.51] & [-0.09, 0.04] & [-0.14, 0.14] \\ \times & 0 & [-0.01, 0.01] \\ \times & \times & [-0.01, 0.03] \end{bmatrix}$$

where

$$\varepsilon^{m}_{\alpha\beta} = \sum_{f=e,u,d} \left\langle \frac{Y_f}{Y_e} \right\rangle \varepsilon^{f}_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + Y_u \varepsilon^{u}_{\alpha\beta} + Y_d \varepsilon^{d}_{\alpha\beta}$$

In the case of $\nu$'s interacting with the Earth matter:

$$\varepsilon^{m}_{\alpha\beta} \approx \varepsilon^{e}_{\alpha\beta} + 3.051\varepsilon^{u}_{\alpha\beta} + 3.102\varepsilon^{d}_{\alpha\beta}$$

Thus, the less constrained and non-diagonal NSI coupling is $\varepsilon^{m}_{e\tau} \sim \mathcal{O}(1)$.

For a complete set of constrains on $\varepsilon^{f=e}_{\alpha\beta}$ see table III in Ref:
O.G Miranda *et al.* (NJP **17**(2015))

# Outline

# NSI in SBL reactor experiments

J. Kopp *et al.* (PRD **77** (2008)) arxiv:0705.2595

- Production (Detection) $\Longleftrightarrow$ $\beta(\beta^{-1})$-decay process.
- At the quark level $u \Longleftrightarrow d$.
- NC matter effects in neutrino propagation can be neglected, so only CC part is present in $\nu$ production and detection.

$$\tilde{\varepsilon}_{\alpha\beta}^{m,f,V\pm A} \to 0 \quad \text{and} \quad \tilde{\varepsilon}_{e\beta}^{S(D),u,d,V\pm A} \to \varepsilon_{e\beta}^{S(D)}$$

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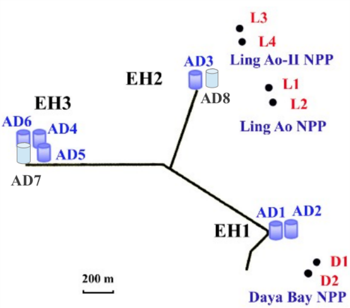
$$\tilde{\varepsilon}_{\alpha\beta}^{m,f,V\pm A} \to 0 \quad \text{and} \quad \tilde{\varepsilon}_{e\beta}^{S(D),u,d,V\pm A} \to \varepsilon_{e\beta}^{S(D)}$$

## Assumptions in the analysis:

- $\varepsilon_{e\alpha}^{s} = \varepsilon_{\alpha e}^{d*} \equiv \varepsilon_\alpha = |\varepsilon_\alpha| e^{i\phi_\alpha}$
- $|\bar{\nu}_\alpha^s\rangle = |\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon_{\alpha\gamma}^{s*} |\bar{\nu}_\gamma\rangle$
- The effective oscillation probability is given by:

$$P^{eff.}_{\bar{\nu}_e^s \to \bar{\nu}_e^d} \simeq 1 + \overbrace{4|\varepsilon_e|\cos\phi_e}^{\text{'zero distance term'}}$$
$$- 4\left[\sin\theta_{13} + s_{23}|\varepsilon_\mu|\cos(\delta - \phi_\mu) + c_{23}|\varepsilon_\tau|\cos(\delta - \phi_\tau)\right]^2 \sin^2\Delta_{31} + \mathcal{O}(\varepsilon)^2$$

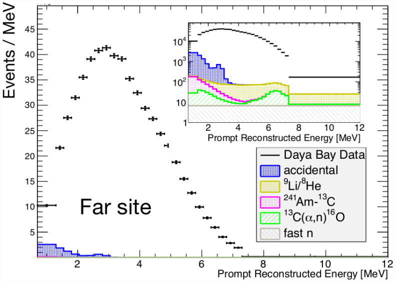
# Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$




$$\frac{N_F}{N_N} = \frac{N_{p,F}}{N_{p,N}} \times \frac{\epsilon_F}{\epsilon_N} \times \frac{L_N^2}{L_F^2} \times \frac{\int \Phi(E)\sigma(E)P_{ee}(E,L_F)}{\int \Phi(E)\sigma(E)P_{ee}(E,L_N)}$$

# Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$

Chao Zhang @neutrino2014




$$\chi^2 = \sum_{d=1}^{8} \frac{\left[M_d - T_d\left(1 + a_{\text{norm}} + \sum_r \omega_r^d \alpha_r + \xi_d\right) + \beta_d\right]^2}{M_d + B_d} + \sum_{r=1}^{6} \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{8}\left(\frac{\xi_d^2}{\sigma_d^2} + \frac{\beta_d^2}{\sigma_B^2}\right) + \left(\frac{a_{\text{norm}}}{\sigma_a}\right)^2$$

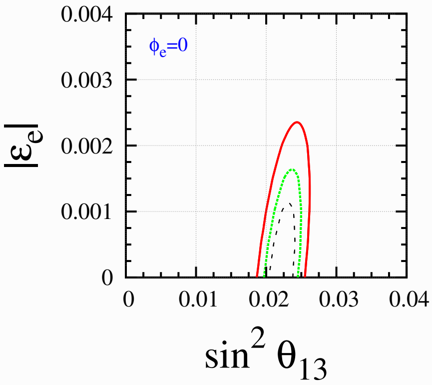
Constrained normalization analysis! $\sigma_a \sim 5\%$.

# Outline

# Results for the $\varepsilon_e$ case

$\boxed{0.020 \leq \sin^2\theta_{13}^{DYB} \leq 0.024}$

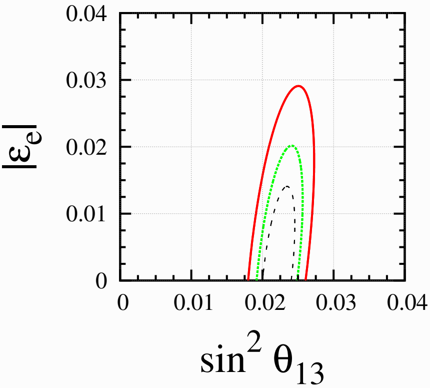
S. Agarwalla *et al.* (JHEP **060** (2015))




C.L = 68.3, 90, 95%; 2 d.o.f

$a_{norm} = 0$
$|\varepsilon_e| \leq 0.0012$ @90% C.L
$0.020 \leq \sin^2\theta_{13} \leq 0.024$

$\sigma_a = 5\%$
$|\varepsilon_e| \leq 0.015$ @90% C.L
$0.020 \leq \sin^2\theta_{13} \leq 0.025$



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# NSI effects at LBL $\nu$-experiments

## Generalizing the effective matter potential

The Standard vacuum neutrino oscillation Hamiltonian is given by:

$$H_0 = \frac{1}{2E}\left[U\,\mathrm{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right)\ U^\dagger\right],$$

while the general matter interaction Hamiltonian can be written as

$$H_{\mathrm{int}} = V \begin{pmatrix} 1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ (\varepsilon^m_{e\mu})^* & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ (\varepsilon^m_{e\tau})^* & (\varepsilon^m_{\mu\tau})^* & \varepsilon^m_{\tau\tau} \end{pmatrix}$$

with $V = \sqrt{2}\,G_F\,N_e$ or $a_{\mathrm{CC}} \equiv 2V\,E = 7.63 \times 10^{-5}\left[\frac{\rho}{\mathrm{gr/cm^3}}\right]\left[\frac{E}{\mathrm{GeV}}\right]$.

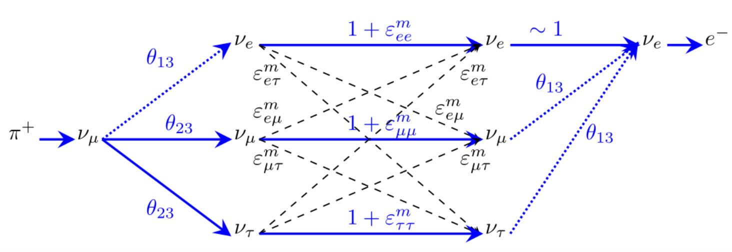
The oscillation probability is obtained as:

$$P_{\nu_\alpha \to \nu_\beta} = \left|\langle\nu_\beta|\exp\left[-i\left(H_0 + H_{\mathrm{int}}\right)\right]|\nu_\alpha\rangle\right|^2$$

# NSI effects at LBL $\nu$-experiments

## (Anti)neutrino appearance

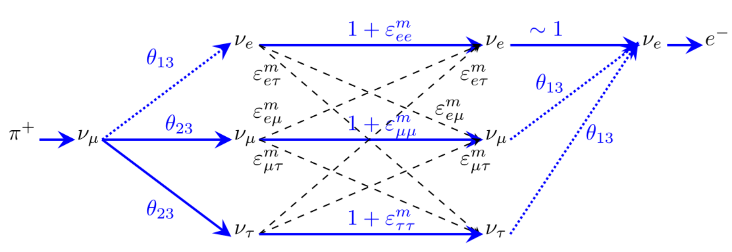
Figure taken from: J. Kopp *et al.* (PRD **77**(2008))



# NSI effects at LBL $\nu$-experiments

## (Anti)neutrino appearance

Figure taken from: J. Kopp *et al.* (PRD **77**(2008))



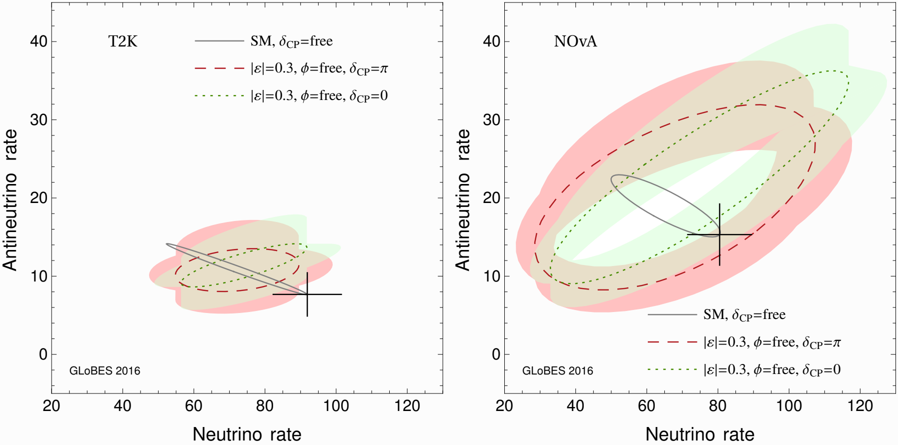

- We will consider only the (Anti)neutrino appearance channel.
- Only the off-diagonal NSI parameter $\varepsilon^m_{e\tau} \equiv |\varepsilon| \exp(i\phi) \neq 0$.
- We simulate true neutrino events including NSI and we compare them to the test SM events in both T2K (scaled 5 yrs) and NoVA ($3\nu$+$3\bar{\nu}$).
- Our results are only for normal MH.

# Outline

# Results

## Bi-rate plots

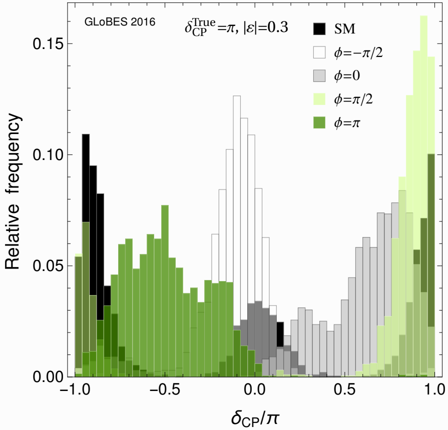
D.V.Forero and P. Huber arxiv:1601.03736

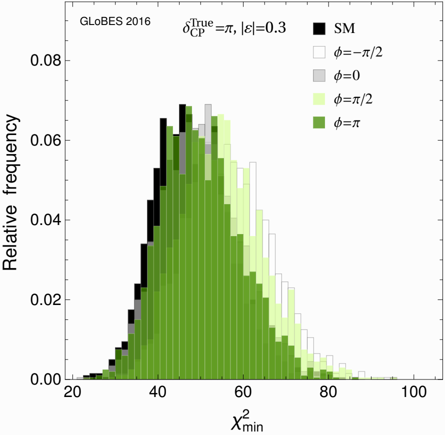


# Results

## Histograms

D.V.Forero and P. Huber arxiv:1601.03736



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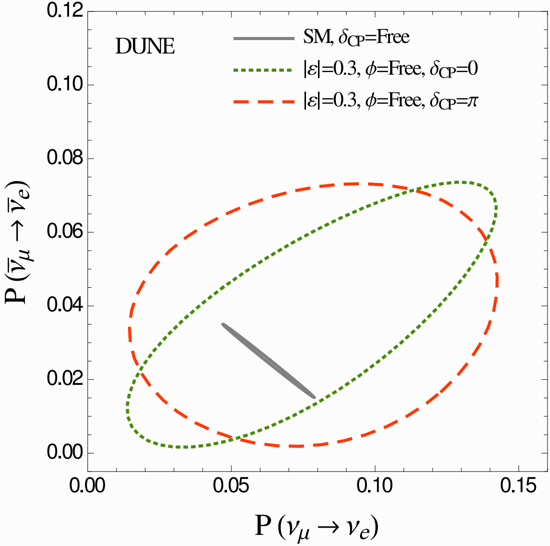
# The future


DUNE
SM, $\delta_{CP}$=Free
$|\varepsilon|$=0.3, $\phi$=Free, $\delta_{CP}$=0
$|\varepsilon|$=0.3, $\phi$=Free, $\delta_{CP}=\pi$
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.00
0.05
0.10
0.15
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$P(\nu_\mu \to \nu_e)$

# What has it been covered...

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THANK YOU